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R. F. SYSTEM FOR FREQUENCY MODULATED CYCLOTRON

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R.F. SYSTEM FOR FREQUENCY MODULATED CYCLOTRON

By K. R. MacKenzie and V. B. Waithman

ABSTRACT

A grounded grid oscillator and a single dee resonant system for use with a frequency modulated cyclotron are described. 7.5 Mev deuterons have been accelerated with dee voltages up to 15 kv and a frequency range from 9.5 to 12 megacycles. 15 Mev protons have been accelerated with voltages up to 11 kv and a frequency range from 19 to 24 megacycles. Coupling constants, phase correction, amplitude modulation and discharge phenomena are discussed.

INTRODUCTION

The frequency modulated oscillators to be described were part of a program undertaken on the 37-inch Berkeley cyclotron[1] to test the theories of Veksler[2] and McMillan.[3] The program was planned in such a way that any results could immediately be applied to the 184-inch cyclotron. To simulate the relativistic increase in mass for a 200 Mev deuteron, the 37-inch cyclotron was shimmed in such a manner that the magnetic field of 15,000 gauss in the center fell off by 13% at the final radius of 18 inches. 11% represented the increase in mass in the 184-inch, and 2% the radial decrease in magnetic field allowed for focussing.*

It was originally estimated that a possible voltage for the 184-inch would be 100 kv on a single dee. The choice of a single dee was made to simplify both the r.f. and mechanical design. If an ion picked up half the full voltage per turn, i.e., 100 kv, it would emerge with 200 Mev after 200 microseconds. This time of flight was chosen as the quantity to retain in the 37-inch design. If a deuteron in the 37-inch cyclotron picked up half the full voltage per turn, it would emerge with 8 Mev in 200 microseconds if the voltage was 4 kv on a single dee. It was decided to provide as much as 10 kv on the dee, but even so the power requirements were quite small.

It was necessary that a frequency range in the ratio 1 to 1.13 be provided with the correct frequency versus time characteristic. Electronic systems were considered briefly. Such systems can be modulated at any speed and theoretically can produce any frequency versus time shape. 10% frequency shifts with approximately 500 volts on the dee were produced with a one kv modulator. However, the power and trouble necessary to produce the desired 10 kv on the dee seemed prohibitive, so attention was turned to a mechanical modulation system.

ROTATING CONDENSER AND COUPLING SYSTEM

The design of a rotary capacitor was undertaken as a separate unit which could be coupled to the dee outside the magnetic field. This allowed design work on the dee and tank to proceed without interruption. In addition, all problems associated with rotation in a magnetic field were eliminated, and it was possible to provide a separate vacuum system for the capacitor. It was initially argued

* Recently the radial decrease in the 184-inch cyclotron has been increased to 4%.

that the better vacuum in a separate system would enable the capacitor to hold more voltage. The design of the capacitor and all these factors affecting the coupling to the dee have been covered in a paper by F. H. Schmidt.[4]

As a result of these considerations, the resonant system as first installled to accelerate deuterons consisted of a dee and capacitor connected by a transmission line. This line was approximately 14 feet long and consisted of a 4-inch circular inner conductor inside a 14-inch square outer conductor. The system operated with a node in the middle of the transmission line and a voltage maximum on the dee and capacitor. This type of system for the proton case is shown in Figure 1. Because of the higher frequency for protons, the line is much shorter and the center conductor is larger in cross section.

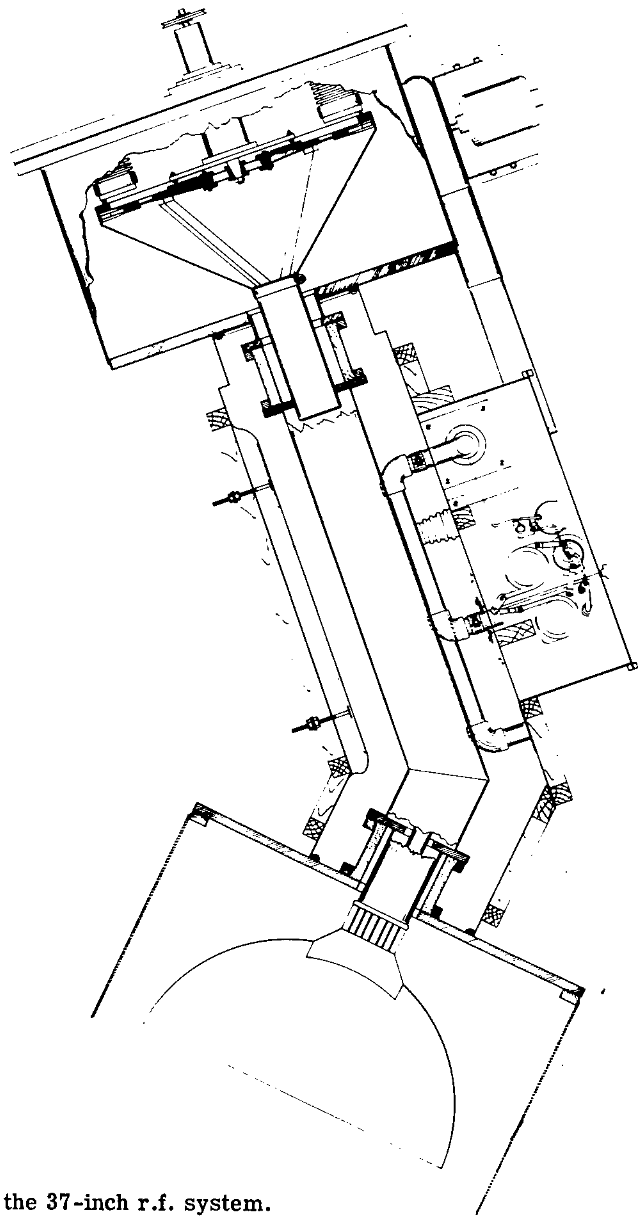

Figure 1. Top view of the 37-inch r.f. system.

The dee capacity turned out to be very close to 300 $\mu\mu$f. In order to keep the capacitor voltage from appreciably exceeding the dee voltage, the minimum capacity was made approximately equal to the dee capacity. While a frequency shift in the ratio 1 to 1.13 is all that is theoretically necessary, the rotary capacitor was constructed to handle a frequency ratio of 1 to 1.25 in order that the shape of the frequency time characteristic throughout the acceleration might be varied by using different sections of the curve. This frequency shift was realized with a maximum capacity in the rotary capacitor of 714 $\mu\mu$f

The successful acceleration of deuterons to 7.5 Mev was sufficient basis for converting the 184-inch to a frequency modulated cyclotron. The acceleration of protons was carried out chiefly because of interest in the 15 Mev particles. The r.f. system for protons, however, was more nearly a scaled down version of the 184-inch r.f. system than the 37-inch system for deuterons. For this reason, the proton oscillator received the most attention. Since the same circuit was used at both frequencies and since all the design considerations apply in both cases, it seems sufficient to give a detailed account of the proton case only, with reference to the deuteron case whenever necessary.

OSCILLATOR AND RESONANT SYSTEM

The first oscillator was of the grounded grid type and consisted of 4 Eimac 304TL tubes in parallel. It was used at both 10 mc for deuterons and 20 mc for protons. In both cases it was placed on top of the square outer conductor of the transmission line and coupled magnetically to the inner conductor by plate and filament coupling loops. It would produce 15 kv peak volts on the dee at 10 mc and 9 kv at 20 mc with 6 kw input. This is somewhat less than the tube rating and is due to the fact that the efficiency is not uniform throughout the frequency range. It averages around 70%. These tubes exist with either a single grid terminal or 4 grid terminals connected to a circular band. The type with 4 grid terminals, while no longer generally available, is preferable for grounded grid operation. A photograph of this oscillator is shown in Figure 2.

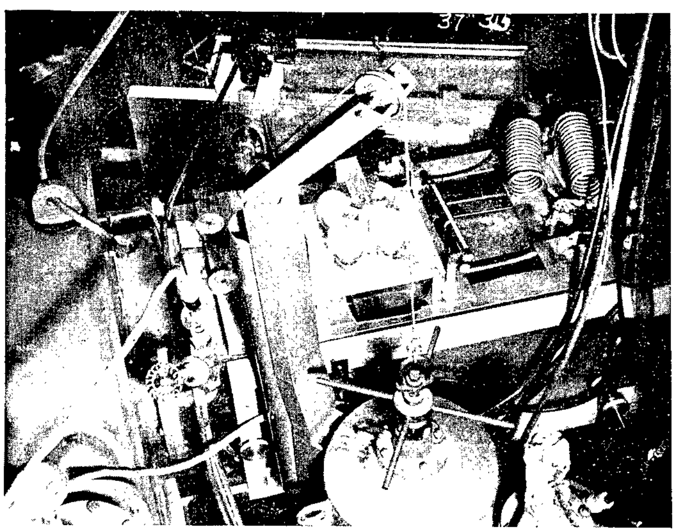

Figure 2. Oscillator using 304TL tubes. The filament coupling loop is a 3/4-inch copper tube which barely enters a slot in the rectangular center conductor of the transmission line. The plate loop is a flat strip which comes within 1/2 inch of the center conductor. The truck which mounts the oscillator using the 3X2500A3 tube is shown pulled away from the side of the transmission line.

Two subsequent oscillators were built for protons. The first of these used an 889 water-cooled tube with 10 kw rated output, and the second used an Eimac 3X2500A3 air-cooled tube rated at 5 kw output. The same housing and components were used in both cases. The same circuit was used in all three oscillators.

The 3X2500A3 is the only one of the above tubes that is specifically designed for grounded grid operation. Had it been available at the beginning of the program, it is probable that the other oscillators would not have been built. The 889 is not particularly suitable for grounded grid operation and gave some trouble with oscillation on the plate loop frequency. This was due to inherent high inductance in the grid leads.

A pictorial circuit diagram is shown in Figure 3. The tube indicated is the 3X2500A3. However, the rest of the circuit applies to any of the three oscillators by substitution of the proper tubes. Since the 3X2500A3 is designed for grounded grid operation, the mechanical layout is much simpler and is easier to describe. For this reason, it will be discussed in preference to the oscillators using the other tubes. Before treating the oscillator in detail, it is necessary to describe the resonant system which it must excite.

An assembly drawing of the parts used to accelerate protons is shown in Figure 1. The transmission line is of large cross section to lower its impedance and allow a sufficient length of line so that the dee and faceplate may be removed from the tank without disturbing the rotary capacitor and its pumping system. The transmission line is bent at an angle to allow the maximum amount of room for apparatus to be placed in the path of the beam. The deflected beam emerges in a direction parallel to the transmission line as shown by the arrow in Figure 1. The design of this r.f. system did not follow any regular pattern. The capacitor had been designed as a unit[4] and had been used for some months while accelerating deuterons. When the decision to convert to protons was made, the reactances of the dee and condenser were measured at 25 megacycles and a section of low impedance line designed which would make the system resonant at this frequency and yet be long enough to be mechanically convenient. To reduce unnecessary inductance and thus lengthen the line, the dee stem section and insulator were made as large as possible and still mount on the 12-inch faceplate. The dee is supported by a 2-inch tube which is fastened to the insulator flange by adjusting screws and sylphon. The path for the r.f. current is over the larger 6-inch tube and through 0.005-inch flexible copper strips which connect this tube to the dee. At the other end of the line, the inductance of the straps connecting the condenser stator ring to the transmission line could not be appreciably reduced without adding to the minimum capacity and reducing the frequency range.

The dee insulator was originally made of porcelain. After one failure due to heat, it was replaced with zircon and although it still gets warm, the temperature rise is not at all dangerous. Cooling water enters the center conductor through insulating hose and cools the dee, rotary condenser, and insulator flanges.

The center conductor has an 8-inch by 14-inch rectangular cross section. The outer conductor, or housing, has a 20-inch square cross section and is made of thin copper sheet nailed to a light wood framework. All joints that must be broken are backed with sponge rubber so that the copper sheets make good contact all along a joint. This is done to minimize radiation and consequent interference which would be particularly objectionable due to the wide frequency band which is covered. The upper and lower frequency limits can be varied together about 6% by a tuning vane which varies the impedance of the transmission line. It is a movable copper sheet with flexible end connections which can be moved toward the center conductor on the side opposite the oscillator.

In spite of the large cross section of the line, the power requirement is 5 kw output for 10 kv on the dee. Some power is lost in the constriction through the insulator on the faceplate and the flexible straps which connect the stem to the dee. A considerable part of the power loss occurs in the rotary vacuum condenser and is due to regions of small cross section and exposed steel. For several months of operation all surfaces in the condenser were steel. At 10 megacycles the heating

was moderate and not sufficient to warrant plating or water cooling. It was tried this way at 20 megacycles, but it soon became necessary to copper plate most of the surfaces. In addition, water cooling was provided on the stator ring and the grounded half of the coupling capacitor.

As mentioned earlier, the 304TL oscillator is mounted on top of the transmission line. It functions as a standby unit. The oscillator using the 3X2500A3 is mounted on a truck which can be

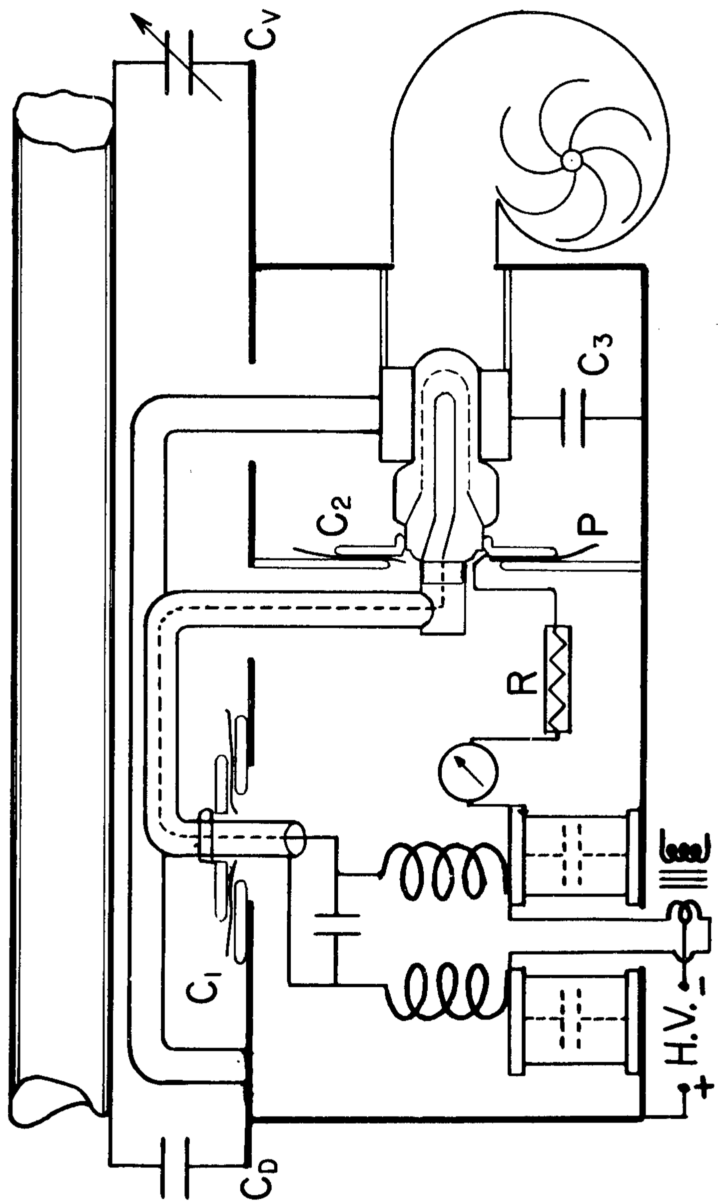

Figure 3. Oscillator circuit diagram. C_1, phase correction capacitor 220 $\mu\mu$f; C_3, 1800 $\mu\mu$f; C_1, 15 $\mu\mu$f; C_D, dee capacity 300 $\mu\mu$f; Cv, vacuum capacitor 290 to 714 $\mu\mu$f; R, 1000 ohms; P, 0.010 inch polystyrene sheet.

wheeled up to the transmission line from the side. Two views of this oscillator are shown in Figures 4 and 5. Contact with the line is made by three large handscrews which tighten rubber-backed connections along the vertical joints. The horizontal joints are also rubber backed, but no particular care is necessary to insure contact as the current flow is parallel to the joint.

The coupling loops are 9 inches apart in the vertical direction and partly enter two horizont slots cut in the 14-inch side of the center conductor. These slots are visible in the left hand portion of the photograph (Figure 4) and also in Figure 5. The purpose of the slots is to allow tight coupling

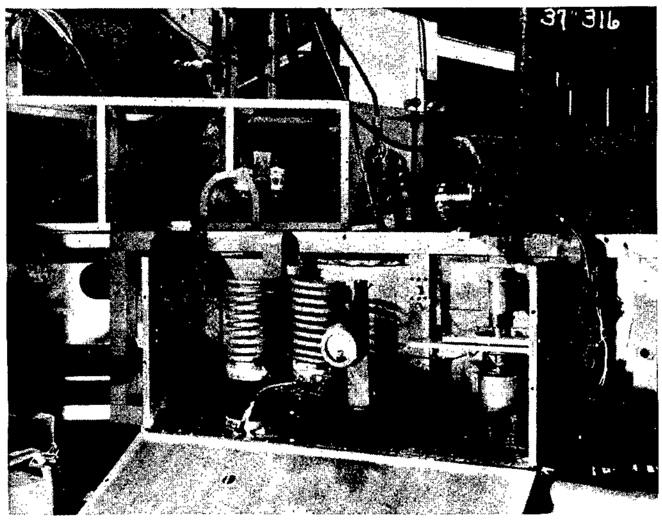

Figure 4. Oscillator using 3X2500A3 tube pulled away from the side of the transmission line to show slots in center conductor. Standby oscillator using 304TL tubes is shown on top of the line.

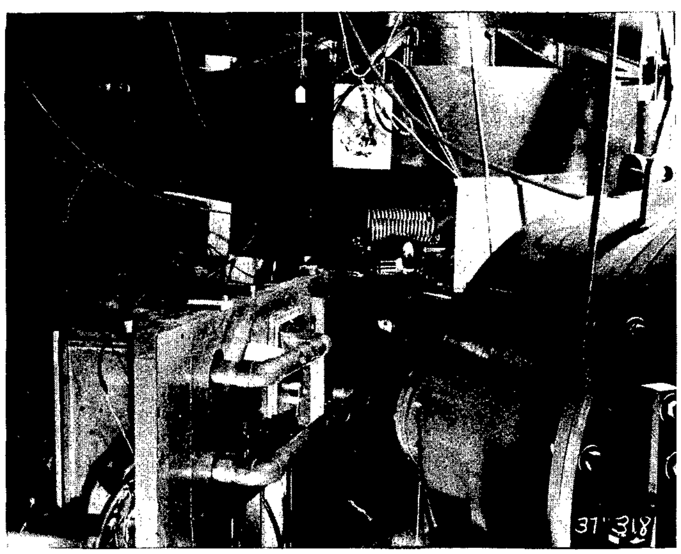

Figure 5. Another view of oscillator showing coupling loops.

and also provide sufficient clearance to prevent sparking to the center conductor. Slightly tighter coupling can be obtained by making the loops project well into the slots, but this has the disadvantage of rapidly increasing the self inductance of the loops. Because of the 9-inch spacing between loops, the coupling between them is insufficient to excite the mode of oscillation in which the plate loop is the principal circuit element.

The grid is grounded for r.f. by means of a low inductance capacitor consisting of a flat metal ring surrounding the tube. This ring has 1/8 inch radius edges and is insulated from ground on both sides by polystyrene sheets 0.010 inches thick. Polystyrene of this thickness used in this manner will stand over 15,000 volts DC and approximately 1500 volts r.f. provided the metal parts remain cool. It was found necessary to water cool the ground slide of this capacitor since the hot air from the anode radiator blows directly against it. The capacity of this condenser is 1800 $\mu\mu$f and the voltage developed across it is 70 volts. A much larger capacity can be used, but if it is too large, grid blocking oscillations will set in due to a large RC time constant.[5] This is especially true with a low Q circuit. Such oscillations will usually not occur if the time constant of the resonant system is more than ten times the time constant of the grid leak grid condenser network.

One end of the plate loop is grounded. This means that both the grid and filament are at a high negative voltage. For water-cooled tubes, this has the advantage that the conductivity of the water is of no importance. It also means that no plate loop by-pass condenser is needed. Of course, the problem is merely shifted to the filament circuit, but here the by-pass condenser carries much less r.f. current and, in addition, serves the important function of correcting phase angles.

PHASE OF THE EXCITATION

In a grounded grid oscillator the phase shift between r.f. plate and filament voltages can easily reach 20° or more if no correction is made. Most of the shift occurs in the filament driving circuit. In Figure 6 the magnitude of this shift for the oscillator using the 3X2500A3 tube is estimated. The phase correction is indicated by dotted lines. As it is not necessary to reduce the shift exactly to zero, the quantities which were used to make this estimate were measured very approximately.

The filament grid capacity is 48 $\mu\mu$f which represents a reactance of 165 ohms at 20 megacycles. At a peak excitation voltage of 700 volts the peak current through this capacitive reactance will be 4.2 amps. The total DC emission from the filament for maximum operating conditions will consist of 2 amp plate current and 0.4 amp grid current. This means the peak fundamental component at 20 megacycles will be approximately 4.4 amp.[6] The resultant current of 6.1 amps will lead the excitation voltage by 43° as shown in Figure 6 (a). Due to the self inductance of the loop, which is around 1/4 μh a back emf of 185 volts is induced which will in turn lead this current by 90°. The vector sum of this voltage and the excitation voltage gives us the emf which must be induced in the loop by the current flowing in the dee stem. From Figure 6 (a) this emf is 575 volts. The phase shift between this driving emf and the excitation voltage is approximately 14°. A similar diagram is shown in Figure 6 (b) for the plate loop circuit. With 4000 volts r.f. across 50 $\mu\mu$f total plate to ground capacity, the current is 25 amp. The peak r.f. electron current is 3.7 amp. The back emf produced by the resultant current of 25.3 amps flowing through the loop inductance of 0.6 μh is 1900 volts, and produces a shift of 7° between plate voltage and driving emf. Here, however, the plate current is 180° out of phase with the plate voltage so the shift is in the opposite direction. The driving emf's (Mwi), induced in both loop circuits by the current flowing in the dee stem, are in phase with each other. Hence, the total shift between plate and filament voltages is 21°. The correction is made in the filament circuit by inserting a capacitor of 140 $\mu\mu$f (c_1 in Figure 3) in series with the loop. The voltage developed across the capacitor lags the current of 6.1 amps by 90° and is shown by the dotted vector "g" in Figure 6 (a). The dotted vector "h" is the new driving emf which is required. The filament and plate voltages in Figure 6 (a) and Figure 6 (b) now lead the driving emf's by the same angle and are therefore in phase with each other.

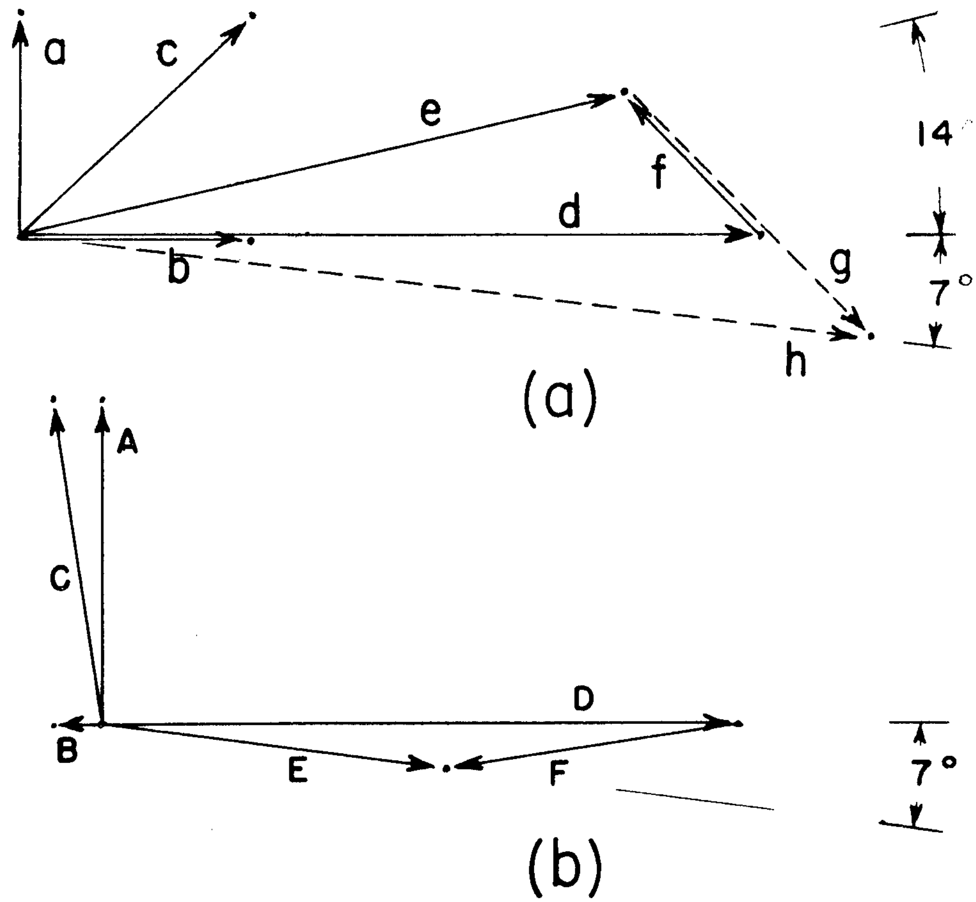

Figure 6. Phase relations between filament and plate voltages. a, 4.2 amp; b, 4.4 amp; c, 6.1 amp; d, 700 volts; e, 575 volts; f, 185 volts; g, 330 volts; h, 810 volts; A, 25 amp; B, 3.7 amp; C, 25.8 amp; D, 4000 volts; E, 2200 volts; F, 1900 volts.

In addition to the approximations already made, the correction is inherently an approximation at other frequencies than 20 megacycles. The capacity (c_1 Figure 3) used in the actual installation is around 220 $\mu\mu$f, part of which serves to neutralize the inductance of the filament chokes. It was made adjustable over a small range and varied until minimum plate current was obtained. This capacitor consisted of a fixed and movable plate separated by air and 0.010 inch of polystyrene. These plates and the adjusting rod that separates them are shown in Figure 1.

It is evident that the lower the inductances of the filament and plate loops, the smaller the phase shift. The loops are therefore made of large diameter tubing and the length of tubing which is not serving as mutual inductance in the dee stem circuit is kept at a minimum. This mutual inductance is practically proportional to the area enclosed by the loop. Variation of the excitation voltage is obtained by a shorting strap which changes the area of the filament loop. Since variation of the phase changing capacitor will also change the excitation voltage, the phase correction is not an independent adjustment.

Another common way to reduce phase shifts is to increase the ratio of capacitive current to electron emission current by adding capacity between filament and grid. However, this lowers the resonant frequency of this circuit. In order that the excitation should vary as little as possible over the frequency range, the frequency of the filament loop is set as far above the cyclotron frequency as possible. This requirement makes it undesirable to reduce phase shifts in this manner.

AMPLITUDE MODULATION

Several factors determine the characteristics of the plate loop circuit. As mentioned earlier, the 37-inch system for protons requires approximately 5 kw output to reach 10 kv peak on the dee. Since the Eimac 3X2500A3 is rated at 5 kw output at 4 kv DC plate voltage, the loop must be large enough to have approximately 4 kv of r.f. on the plate for 10 kv on the dee. Since one end is grounded, it was a simple matter to change the length to achieve this. The resonant frequency of this loop circuit must be as far as possible from the cyclotron frequency so that the relative voltages on the dee and loop will stay fairly constant over the desired frequency range. But, as the frequency varies, it is also important that the plate loop frequency does not coincide with harmonics of the fundamental. If this happens, the plate loop frequency is strongly excited and the amplitude of the fundamental decreases. With the arrangement in Figure 1, the fundamental shifts from 19 to 24 megacycles. The first harmonic shifts from 38 to 48 megacycles and the second harmonic from 57 to 72 megacycles. Because of the limitations imposed by tube capacity and necessary loop size, the frequency of the plate loop could not be made higher than 38 megacycles. At one point this will coincide with the first harmonic. Figure 7 (curve a) shows the amplitude variation as the funda-

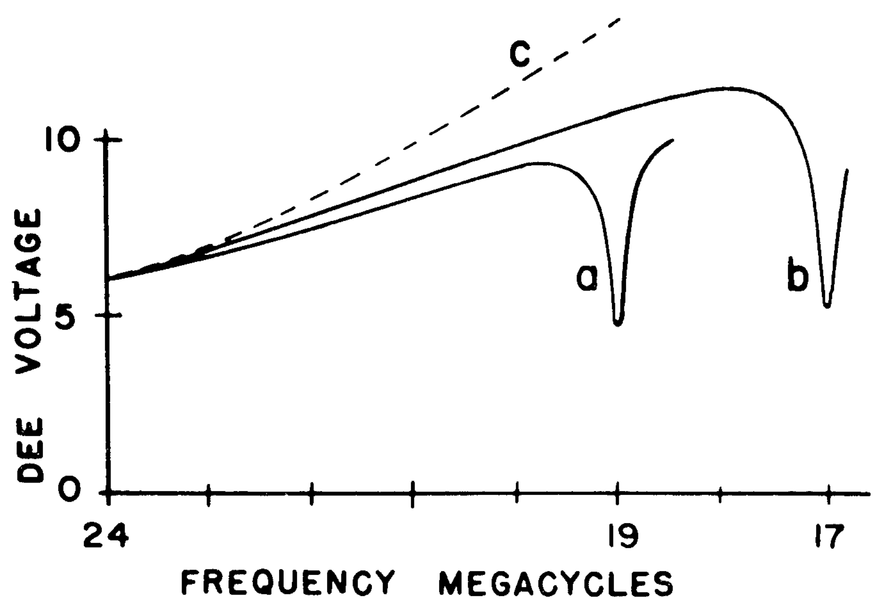

Figure 7. Amplitude modulation as a function of frequency.

mental frequency goes through 19 megacycles. It has been predicted theoretically and demonstrated experimentally that most of the ions can be lost by such a variation if the ions reach their final radius at 19 megacycles. It was therefore necessary to add about 15 $\mu\mu$f to this circuit, which

lowered its frequency to 34 megacycles. The variation is shown in Figure 7 (curve b). The extreme dip in amplitude at 17 megacycles is outside the frequency range and does no harm. It should be noted that lowering the loop frequency by adding capacity will reduce the phase shift, while lowering the frequency by adding inductance will increase the phase shift.

Actually there will be a dip in the amplitude of the fundamental whenever one of the higher order modes of the r.f. system coincides with a harmonic of the fundamental. The plate loop frequency referred to in the preceding paragraph was measured when coupled to the dee stem and is, therefore, a higher order mode of the system. Any coincidence higher than the second harmonic, however, produces dips of the order 5 to 10% which can be ignored. With a high Q system, the dips are still further reduced during rotation of the vacuum condenser since the stored energy maintains the voltage during the short interval that the coincidence occurs.

The general form of the amplitude variation shown in Figure 7 is explained as follows: The rotary condenser dee system and the plate loop can be treated as two coupled circuit with lumped capacities and inductances.

If i_1 and i_2 are the currents in the dee stem and plate loop respectively, the ratio of dee voltage to plate voltage is

$$Vd/Vp = i_1Cp/i_2Cd$$

where Cp is the plate to ground capacity and Cd is the dee capacity. Neglecting resistances

$$i_1/i_2 = j(Lpw-1/Cpw) \;/\; (-jwM) = -\,\text{const.}\,(1-1/LpCpw^2) = -\,\text{const.}\,(1-w^2p/w^2)$$

where Lp is the inductance of the plate loop and Wp is the resonant frequency of the plate loop which is set at 34 megacycles. Therefore,

$$Vd/Vp = -\,\text{const.}\,(1-wp^2/w^2)$$

Substitution of 19 and 24 megacycles gives a dee voltage ratio of 2.3 to 1 for constant r.f. plate voltage. This variation is shown by the dotted curve in Figure 7.

Several effects combine to reduce this voltage ratio. (1) Since the dee is an appreciable fraction of a wavelength, the voltage difference between front and back of the dee will be larger at 25 megacycles than at 20 megacycles. The voltage on the front edge of the dee will therefore vary some-somewhat less than 2.3 to 1 at the two frequency limits. (2) Less power will be required at 24 megacycles due to the lower dee voltage. The result is higher tube efficiency and larger plate r.f. swing than at 19 megacycles. The dee voltage will increase in the same ratio as the increase in plate r.f. voltage. (3) At the low frequency end of the range the first harmonic is approaching the plate loop resonance which reduces the power in the fundamental (Figure 7, curve b). These effects reduce the ratio to approximately 1.6 to 1. At the full power input of 9 kw this ratio is further reduced to about 1.4 to 1 since the emission limitation of the tube at the low frequency end of the modulation cycle is reached before the average plate dissipation is exceeded. However, the ratio can be increased as much as desired by arbitrarily lowering the frequency of the plate loop. This type of amplitude modulation* was desired at the time the oscillator was designed and led to the choice of this circuit. Other circuits using transmission line coupling to the dee stem have been tested which keep the dee voltage relatively constant for constant plate voltage. These circuits, however, have not yet been used on the cyclotron.

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*A theory developed by J. R. Richardson just prior to the 37-inch test called for a rising voltage characteristic. Recent work by D. Bohm, L. L. Foldy, and L. R. Henrich (to be published) based on different arguments, predicts the disirability of such a voltage rise for the 184-inch cyclotron, where the magnetic field decreased linearly with radius.

Provision was made for arbitrary amplitude modulation by inserting an 893 triode in series with the power supply lead. As yet it has not been used for this purpose, but as it has a 20 kw plate dissipation, it has been used as an emission limiting device to protect the oscillator tubes when discharges occur in the tank and condenser.

DISCHARGES IN THE ROTARY CONDENSER

Initially, some trouble was experienced with a type of discharge that occurs only at low r.f. voltages, and, therefore, prevents the oscillator from driving the dee to high r.f. voltages where the discharge does not occur. At 20 megacycles the space between electrodes which will allow an electron to reach an energy around 30 volts in 5 cm. There are very few paths, along the magnetic field, in the neighborhood of the dee that are greater than this, so no trouble has occurred in this region. In the rotary condenser however, (see Figure 1) most of the paths are of the order of 20 cm. Electrons oscillating in this space can reach efficient ionizing energies long before their amplitude becomes equal to the distance between electrodes. Above this voltage, which is in the neighborhood of 500 volts, the discharge is rapidly extinguished as electrons can no longer oscillate. However, the discharge is usually intense enough, even at 10^{-5} mm of Hg to prevent the voltage from building up to this extinction value. Such a discharge can be eliminated by a sweeping field obtained in any manner. The sweeping field was obtained on the 37-inch cyclotron by biasing the dee, transmission line, and condenser stator parts a few hundred volts positive. For reasons which are not clearly understood this bias usually increases the size of the beam by a factor of two or more.

Other methods for quenching this type of discharge include the use of a "tickler" oscillator. Since the tickler oscillator does not derive its excitation from the load, it can drive the main oscillator over the critical voltage. Such a device was used by J. B. Backus on the 60-inch Berkeley cyclotron to enable the oscillator to "ride through" a similar discharge in the large volume around the dee stems.

CONCLUSION

The design of the 184-inch cyclotron has been based on the work done with the 37-inch. An oscillator similar to the one on the 37-inch has been designed with 75 kw output and is expected to produce 40 to 50 kv on the dee with a frequency range from 9.5 to 12.5 megacycles. Throughout this work the authors have been indebted to Professor E. O. Lawrence and the staff of the Radiation Laboratory for continued interest, advice, and encouragement. In particular, the suggestions of F. H. Schmidt, John R. Woodyard, J. R. Richardson, and W. R. Baker have proved most helpful.

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